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Impact of nanotechnology advances in ICT on sustainability and energy efficiency☆

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ABSTRACT

Urbanization, sustainability, energy efficiency, information and communication technology (ICT) and nanotechnology are emerging at the beginning of the 21st century. They are seeking to improve environmental effectiveness in the context of connected communities, global competitiveness, economic development, climate change, and demographic shifts. Virtually all proposed solutions to energy consumption and climate change acknowledge the role ICT plays as a key enabler of environmental effectiveness. One of the major challenges that the ICT sector faces today is that hardware is being pushed to its physical limits. The traditional means to reduce product size, increase functionality and enhance computing capabilities are becoming difficult and expensive every passing day. On the other hand, the industry is benefiting from nanotechnology advances with numerous applications including those in smarter sensors, logic elements, computer chips, memory storage devices, optoelectronics, quantum computing, etc. This paper presents an overview of the ICT benefiting from development in nanotechnology with respect to sustainability and energy efficiency.

Contents

1. Introduction

Environmental sustainability is a very hot topic at the moment. Topics such as climate change and global warming have generated a lot of discussion and even some international regulations aimed at reducing the human environmental load [1]. This is the urban century—more people worldwide are living in urban areas than rural for the first time in recorded history. The urbanization trend picked up pace in the 20th century and has accelerated since. Whereas in 1950 only about 30 percent of the world's population lived in cities, today it is more than 50 percent. Urbanization manifests itself in two ways: expansion of existing cities and creation of new ones [2].

Cities are already the source of close to 80 percent of global CO_2 emissions and will account for an ever-higher percentage in the coming years, as more and more people reside in and move

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to cities in search of prosperity. If we continue with the same solutions that have been used to address urban development needs in the past, the resulting urban ecological footprint will not be sustainable—humanity will need the equivalent of two planets to maintain those lifestyles by the 2030s. At the heart of the matter, we face a challenge of meeting demands of urbanization in an economically viable, socially inclusive, and environmentally sustainable fashion [2,19].

Urbanization is an inevitable progression. It can go well, it can happen badly, but progress it will. To make urbanization a positive and productive transformation that will deliver long-term gains to citizens, three goals need to be achieved—social equitability, economic viability, and environmental sustainability. Social equitability is based on the principle of inclusion; there is no discrimination in access to benefits across population segments. Economically viable solutions are those that are financially self-sustaining. Environmental sustainability ensures the preservation of the environment for future generations [2].

According [3], most of the attention in sustainable urban development has been directed to three sectors: buildings, energy, and mobility. Today, however, it is becoming evident that a fourth, equally important element must be addressed: ICT. When it comes to urban sustainability, ICT is part of the problem (based on its contribution to overall energy consumption), but an even bigger element of the solution. ICT is a significant contributor to energy efficiency: for every extra kilowatt-hour of electricity demanded by ICT, the U.S. economy increases its overall energy savings by a factor of ten [4].

World is facing an increasing scarcity of raw material supply in various fields. In order to reduce the energy and carbon burden linked to building materials and components, Knowledge Society will see an increasing pressure on their sustainable performance, i.e. longer service life, multi-functionality as a primary step to create added-value of material use, more efficient use of primary raw materials, an increase in recycling as well as an increasing use of renewables. In addition, the application of lightweight materials and systems will be inevitable to reduce the environmental impact of the construction process. Particularly with respect to the last two issues, the scarcity of resources will be a restraining factor. As energy demand for the operational phase of the building life cycle is decreasing and/or for a larger part covered by renewable energy, the embodied energy of building materials and components will become an increasingly important aspect to take into account. The present ratio between embodied energy and energy during the use phase of a building is about 20/80. Because of the way the building industry is organized, decision-makers/investors in e.g. energy saving or sustainable energy are not the ones who benefit from the gains that these can provide. As a result of this imbalance, market forces do not provide any strong incentives towards Life-Cycle-Costing for buildings, and breakthroughs are only likely if regulations are also set in place. Because cost optimization is to a large extent linked with optimization of the required amount of man-power, more and more use will be made of prefabrication and ICT (e.g. Building Information Models) in the building process [5].

Materials have to be manufactured on demand today, meeting the complex set of the specific requirements. Embodied energy (emergy) in materials represent a relatively high percentage of energy throughout the life cycle of buildings, especially when increasing the level of energy performance in operation. New approaches combining novel processes, sensors and material science are needed to minimize the embodied energy of main construction materials such as cement, concrete, glass, steel, ceramics, etc. Development of new multifunctional materials is needed, having a low embedded energy and also higher thermal and acoustic properties (embodied energy is often proportional to mass), overcoming scarcity of renewable materials. It is becoming more apparent that the next technological frontiers will be opened not through a better understanding and application of a particular material, but rather by understanding and optimizing material combinations and their synergistic function, hence blurring the distinction between a material and a functional device comprised of distinct materials. Future research will be strongly focused on the final performance properties and less on the individual material performance. New technology routes to integrate waste in the production cycle (recycling) of materials are needed [5,20].

The remainder of this paper is organized as follows. Section 2 explains role of ICT in sustainability and energy efficiency in urban communities and Section 3 presents a quick overview of materials and properties. Section 4 details developmental trends in nanotechnology and applications in the ICT sector. Finally, Section 5 summarizes future trends of the ICT in the context of sustainability and energy efficiency.

2. Role of ICT in sustainability and energy efficiency

A new dimension has been added to the world of information and communication technologies: from *anytime, any place* connectivity for *anyone*, we will now have connectivity for *anything*. Billions connections create an entirely new dynamic network of networks – an Internet of Things (IoT).The Internet of Things is a technological revolution that represents the future of computing and communications, and its development depends on dynamic technical innovation in a number of important fields, from wireless sensors to nanotechnology [15]. Leading technology companies in the world, such as Cisco, Microsoft, and IBM, have recognized the value of the global information infrastructure and they are offering their solutions. Virtually all proposed solutions to energy consumption and climate change acknowledge the role ICT plays as a key enabler of environmental effectiveness in large metropolitan areas (Stern, 2006; IPCC, 2001, 2007). The SMART 2020 report (The Climate Group, 2008) addresses exactly *how* urban ICT and broadband connectivity can help, and what the carbon-reduction impact of innovative urban ICT policy for energy efficiency can be. Any discussion of sustainable urban development must acknowledge that ICT is part of the problem facing cities today, based on its ever-increasing levels of energy consumption. This downside, however, is more than mitigated by its valuable contributions to energy efficiency, its ability to reduce energy demand in other activities (e.g., using teleworking to reduce trips to the office), and the existence of ICT applications that increase the efficiency of energy used in these activities (e.g., car routing that cuts traffic congestion) [3,21].

The ICT infrastructure (servers, storage, networks, and the IT team) supporting the city domains is not operating in an integrated and coordinated manner. Having these silos of ICT infrastructure often leads to increased cost of operation, underused and overused hardware, and redundant software. These ICT infrastructure issues might be less obvious, but they are an important aspect of cutting costs, providing more openness, and streamlining operations [6,16].

It should be no surprise that, as the society moves into the digital realm and uses more instrumentation, there will be a lot of data. You might find the following common challenges, among others, when handling data:

- A need for data from various sources to get an accurate view of an event or potential situation. The data must be collected, stored, transformed, and analysed to provide actionable information.
- Data security, including proper governance, such as audit trails and controlled access.
- Management of the data life cycle such that data is collected, stored, transformed, and archived properly [6].

To generate new insights from the exploding volume, velocity, and variety of data, IT departments need systems that are architected for that task. These workloads can place tremendous demands on the systems used to process the transactions and complete the computing tasks. This environment must be able to handle the following tasks:

- Design a system architecture that is flexible, able to handle new and complex workloads, and responds to changing needs and growth.
- Ensure service delivery with 24×7 availability.
- Provide security against cyber attacks, malware, and other potential security breaches while still supporting an open environment.
- Handle and recover from failures while minimizing the loss of time and data [6].

Solutions currently in progress target the following areas:

- Increasing efficiency of traffic flows
- Improving efficiency, service offerings, and manageability of public transportation
- Creating sustainable real estate models that incorporate energy efficiency and new work environment models (remote worker, collaboration, shared space, etc.)
- Establishing new, distributed delivery models for city services to residents
- Enabling new resident services to self-manage carbon footprint [3].

2.1. ICT as a critical infrastructure

Many ICTs will have matured, and ICTs will be widely used and inextricably linked to everything we do. As a result their transformative impact will be visible in every area of life. ICTs will provide the basic infrastructure for *all* vital social and economic processes. Every commercial and public service will be provided through and shaped by this e-Infrastructure. ICTs will be indispensable to address the key challenges that society is facing, in for instance urban planning, transport and logistics, in crime prevention and risk management, in health care and in coping with scarce resources. And, last but not least, ICTs will continue to play a defining role in our economy by providing critical infrastructure for the global economy. It will function more and more as a 'system of systems' [7].

With the maturation of silicon technology new emerging trends will shift into the focus such as:

- The development of new concepts and architectures for computing;
- The utilitization of advanced ICTs for "non-computing" purposes;
- The search for non-silicon processing and memory technologies;
- The increasing role of photonics (the use of light will enable new disruptive innovations in the field of healthcare, manufacturing and security, and may reduce dependency on energy) [7].

According to a report published by the Information Society Advisory Group (ISTAG), the current convergence of information, communication and media technology and services is at the basis of this highly integrated e-Infrastructure that will shape the future of the knowledge society. The future e-Infrastructure will be the key platform for the development and deployment of innovative, efficient and attractive knowledge society services. The development of this infrastructure poses us with important challenges. It is more than network connectivity; it also includes basic application services. Development and deployment need to be better integrated, particularly from the perspective of users. It also calls for regulatory frameworks covering issues such as ownership of personal data, open standards, sustainable IPR and competitiveness in the market. The successful development of this e-Infrastructure requires alignment of public and private interests. It brings about complex coordination and governance issues. R&D efforts both need to address critical e-Infrastructure technology components and focus on the development and deployment of applications and services. Furthermore, convergence also underlies the growing importance of media and content in the ICT-field [7].

The pervasive impact of ICTs will also change the drivers for innovation. Historical research on technological disruptions suggests that general-purpose technologies often develop through three qualitatively different phases. The first *concept-centric* phase kicks-off when radically new technical opportunities emerge, resulting first in a large variety of product concepts and then in a dominant design. In the next *product-centric* phase, the dominant design and its production processes are optimized using the performance criteria implicit in the dominant design. When product performance starts to exceed the requirements of many users, a *user-centric* phase of development emerges, with an increasing focus on users, their differentiated needs, and on the convenience of use [7].

We have seen this sequence of stages in many industries such as electrical lighting, automobiles, and consumer electronics and it may now also be observed in ICT innovation. A substantial part of the ICT industry is currently moving *beyond* the user-centric phase, towards what we may label the *infra-centric* or *society-centric* phase. In this phase, technology becomes a vital infrastructure that is of critical importance to society. In this stage, the drivers for innovation, improvement and progress are foremost *socially defined.* The infrastructure becomes an issue of the highest societal concern and *social innovation* a main driver for ICT development. Evidently, this does not mean that there is no longer any product- or user-oriented technology development: what we imply here is that a shift is taking place towards innovation that is primarily society-driven [7].

In this phase, progress can no longer be measured by merely using technical criteria. Let us take the computing industry as an example: progress is no longer defined by faster processor clockspeeds and more bits. Instead, the criteria for measuring development are now more society oriented and are consequently more and more defined *outside* the technical developer community. In this cycle of innovation, challenges are rephrased: "more power" may first be described as "longer battery life", next as "greater usability" and then as "less battery power and carbon emissions" [7].

In the case of ICT, the constraints are infrastructure components—servers, images, virtual machines, memory, bandwidth, and so on—that control the speed with which valuable business output can be produced [8].

3. New technological development

Contiounus innovations in ICT sector have enabled the development of new high-tech products and services, new investments, and new ways of doing things. Even without further technical development, the wide deployment of ICTs will have disruptive societal implications, as ICTs are more and more inextricably interwoven with every aspect of our lives. But technical innovation in the ICT-field will not at all slow down. New ICT-paradigms will come up, with new opportunities for high-impact research, technology development and innovation. The extremely fast incremental improvements that we have seen in the past (based on continuous miniaturization of components on integrated circuits), will probably slow down. But alternative technical developments will come to the fore—for instance when highly detailed contextual data will be more and more connected to biological and neural information on human beings—introducing new disruptive transformations [7,22].

Let us illustrate this by describing developments in the basic semiconductor technology. At present, integrated circuit technology is entering a new disruptive phase. For almost five decades now, integrated circuit technology has progressed at a speed probably outpacing any other known technology in the human history. The extremely fast incremental improvements in the basic integrated circuit technology that we have seen in the last decades, were based on continuous miniaturization of components on integrated circuits. This improvement will now slow down and hit physical and economic boundaries. This can be overcome only by disruptive innovation. Alternative basic computing technologies and programming models will become increasingly attractive. In the society-centric phase of development that we are entering now, "more of the same" will not be enough. More than before questions such as *why and when* we need more transistors, faster clock speeds, and more bits, will be asked [7].

World is facing with increasing urbanization, emerging digital economy and global warming. In this new stage of community development, new technologies are needed, such as self-organizing, reconfigurable, bio-inspired, nano-inspired, non-deterministic, and cyber-physical processing architectures. ICT will move beyond the silicon-age of the 20th century. Photonic technologies utilizing light will gain importance. Silicon-based high-performance computing will no longer be a dominant driver for technology development, but instead technologies such as opto-electronic and extremely lowenergy devices, including self-powered devices, will gain visibility [7].

The future Knowledge Society is a society in which massive amounts of information and data are being processed and given meaning to. Information and data are generated by sensors, machines and information-enhanced products. This enables action at a distance, which will become common place, whether it means reacting to video and monitor streams from our homes, conducting scientific experiments in international e-collaboratories, making nano-scale devices, having a health check or driving a car in intelligent traffic. Robotics, sensors and autonomous agents will therefore be important elements of this emerging e-Infrastructure. Technological progress will be more than before based on the ability to take human beings in the loop in their social environment, but also including their biological, and neural information [7,22].

4. Nanotechnology

'Nano' is one of the most frequently used buzzwords in the science and technology. Nano is a Greek word which means 'dwarf'. The field of nanotechnology is vast and interdisciplinary, ranging from medicine and healthcare to construction and consumer electronics. For this reason the definition of "nano" may vary and even among experts no consensus can be found today [17]. Nanotechnology, as we now know, has become the driving force of the latest technological advances that truly indicate the phenomenon of excess for less. The physical, chemical and biological manipulation of materials at nano-scale resurges materials with modified properties of colour, magnetism and the electric conductivity, thereby, creating a new gauge for human capabilities on the technological front. The miniaturization revolution that emerged from an atomic and molecular modification concept introduced by Richard Feynman way back in 1959, is today driving the micro- and macro-economics of a varied domain of industry verticals allowing technologists to engineer products with tolerance levels to a millionth of a meter [9].

Nanotechnology's great sustainability promise is to bring about the much needed power shift in renewable energy: a new generation of highly efficient photovoltaics, nanocomposites for stronger and lighter wind energy rotor blades, to name but two; but also a new class of nanomembranes for carbon capture at fossil fuel power plants. Energy savings could be made if the proper nanomaterials were used not just for more efficient distribution and power transmission (and nanosensors might lend a helping hand to the decentralized management of renewable energy grids), but also to build smart glass and electrochromic windows capable of maximizing the use of solar power to heat buildings [10,18].

Nanomaterials can be used to improve the capacity of batteries, solar cells and fuel cells. These are superconducting at room temperatures to reduce the high transmission losses in our centralized energy supply. Energy storage could be greatly enhanced by optimized batteries and supercapacitors, while nanotacalysts could optimize fuel production [10].

Safe water purification, filtration and desalination through cheap and portable nanotechnology systems is a huge hope for a better future which could help developing countries to have their own clean and drinkable water [10].

Nanomembranes, which are organic polymer-based nanocomposites less than 100 nm thick, are effectively filters operating at the molecular level. They are a class unto itself since their work is copied from nature, and indeed living cells use a form of nanomembrane to function. Their properties and optimal use are actively being researched, as in the case of highly selective MIMs (Molecularly Imprinted Materials) with strong membrane permeability and the incorporation of natural aquaporins, which are naturally occurring proteins, into industrial membranes [10].

Nanotechnology is also focusing on researching nanoparticles as powerful adsorbents and nanoscale titanium dioxide as a catalyst to remove contaminants. Nanosilver ceramic filters have already found their way onto market applications due to their antibacterial and antiviral action [10].

Nanotechnology in many respects is already a key player in ICT research and development, in both academia and industry. Computer microprocessors and memory storage devices have followed a path of miniaturization in the last 20 years that has "naturally" brought transistors to have dimensions lower than 100 nm. There are now challenges to meet in continuing this miniaturization path because as the materials of semiconductors, metals and insulators are reduced to nano-size, quantum effects start to predominate and to determine their properties. This is resulting in a number of issues. Nanotechnology offers the opportunity to exploit, rather than avoid, quantum effects for the development of the next generation of integrated circuits. As miniaturization cannot proceed forever with the methods and tools that have been used so far, new approaches will be needed. Nanomaterials, precisely for their quantum properties, and nanotechnology tools allow the creating of new data storage and processing methods [11].

4.1. Nanotechnology in IT Industry

One of the major challenges that the information and communication technology sector faces today is that platforms are being pushed to their physical limits. The traditional means to reduce product size, increase functionality and enhance computing capabilities are becoming difficult and expensive every passing day. However, the industry is benefiting from nanotechnology in more ways than one. The applications are numerous including those in smarter sensors, logic elements, computer chips, memory storage devices, optoelectronics, quantum computing, etc., but can mainly be classified under categories of nanoelectronics and photonics, namely integrated circuits, electronic manufacturing equipment, displays and graphenes, data storages and quantum computing [9].

4.1.1. Integrated circuits

Continuous size reduction of transistors managed to enhance the performance on the grounds of speed, power and cost per function for decades but no longer meets the current application

requirements. Adding on, the semiconductor industry is now focused on performance-per-watt than rating it in giga hertz. New material systems and new device architecture complemented by improvised process control have, thus, gained utmost importance. This is where nanotechnology has made a mark [9].

4.1.2. Electronic device manufacturing

Electronic manufacturing units require demanding environments, higher throughput (number of wafers manufactured per hour) and lower defect rates (defects per sq.cm). The need of ICs with a smaller feature size has resulted in newer manufacturing technologies like atomic layer deposition and NIL (*nanoimprint lithography*). While atomic layer deposition is employed in deposition phase of a manufacturing process to create high k-metal dielectrics, nano imprint lithography is used to provide insulation layers that separate copper interconnects amongst transistors. The technologies are being widely used in optoelectronics, MEMS (*micro-electro-mechanical systems*) and semiconductor materials [9].

4.1.3. Displays and graphene

The most ubiquitous displays are incorporated in electronic devices like PC monitors, notebooks and mobile phones. The two main nanotechnology-enabled display technologies are OLED (*organic light emitting diode*) and FED (*field emission display*). In OLED, the emissive layer is made up of an organic compound. In FED, a carbon nanotube acts as an electron source striking a coloured phosphor. These display technologies are better than conventional CRT in terms of refresh rates (time taken to scan across a pixel) and viewing angles, and also have lower power consumption. The AMOLED (*active matrix organic light emitting diode*) offer even better refresh rates because of the matrix layout of pixels. LCDs are considered to have comparatively higher power consumptions because of the backlit requirement. Talking about the negative aspect, the OLED face challenges in terms of life as organic materials are prone to degradation. A nanotechnology material called graphene is being researched by Samsung to conduct electricity across flexible transparent touchscreens based on a carbon sheet that is just one atom thick and can be folded like paper [9].

4.1.4. Data storage

Nanotechnology-based data storage mainly comprises of MRAM (*magneto-resistive random access memory*), FeRAM (*ferro-electric* RAM), RRAM (*resistive* RAM) and NRAM (*nanotube* RAM). MRAM has the advantage of endurance and wider temperature operation bandwidth. Other advantages of nanotechnology-based data storage include longevity, higher read/write speeds and lower costs [9].

While carbon nanotubes can be used as semiconducting material in data storage, scanning probe microscopes can find utility in data transference applications. For example, IBM's millipede system utilizes an array of AFM (*atomic force microscope*) tips to make indentations in materials, similar to what a laser does while reading a CD. Interestingly, the Nantero trademark NRAM uses the positioning of carbon nanotubes to determine memory states [9].

A recent study by NanoMarkets has projected these storage devices to constitute a $65.7 billion market by the beginning of 2012 [9].

Quantum Computing Nanotechnology is at the base of the concept called Quantum Computing, that can decipher larger volumes of data, clocking faster than current Silicon technology. In spite of encoding data as zeros and ones as in binary computers, the quantum computer stores data as qubits which can store both zeros and ones simultaneously. This significantly reduces the number of computations required for all possible permutations, giving more accurate results using less power and consuming lesser time. Toshiba's quantum dot (a stream of electrons in semiconductor with upward/downward magnetic spin differentiation) LED concept forms the basis of optical quantum computing power [9].

4.2. Thermoelectricity for energy harvesting

Sensor network nodes are typically battery powered and this represents a drawback with respect to traditional wired systems. Batteries need to be periodically replaced or recharged. Such an operation results in increased maintenance costs and for specific applications might be economically unfeasible. In these cases nodes might have to be treated as *disposable* devices; hence in order to avoid costly maintenance procedures new sensor nodes might have to be deployed once the existing ones run out of power. Replacing batteries might be a non-trivial task when nodes are operating in environments with harsh conditions (high temperature or pressure) that are unsuitable for humans. In order to mitigate these problems two directions are currently being investigated. A considerable research effort aims to maximize battery lifetime through energy aware design of sensor's hardware, protocols, and applications. In this regard the use of wireless communications has been identified as the major source of energy consumption for these low power devices. As a result, optimizing the design and usage of the radio subsystem of sensor nodes (motes) is therefore a key issue that has to be addressed. Alternatively, the design of devices with energy harvesting capabilities (i.e. devices that can capture the energy they need from the surrounding environment) is being investigated [12].

Thermoelectricity (TE) [23] is the conversion of heat into electricity (Seebeck effect), or of electricity into heat or refrigeration (Peltier effect). The use of the Seebeck effect could allow heat to be saved which would be otherwise lost. Although the conversion efficiency is very low, it has been enjoying renewed favour for several years, and novel research and development leads have been investigated, such as new materials and the structuring of matter at the nanoscale [13].

It is becoming more and more apparent that thermoelectricity is a promising source of electric power, thanks to its ability to locally scavenge energy by converting a heat flow in electricity, when placing a thermoelectric device in a persistent thermal gradient. Even with a modest conversion yield, this would have huge benefits. As a consequence, many applications are being imagined for local electricity production by the TE effect, thanks to local heat leakages. Since this energy is available anyway, it is possible to estimate the interest of this solution depending on the price of the TE device vs. benefits like reduction in local energy requirements. The other main features of these devices are: the lack of mechanical parts allowing for silent and clean functioning; their small size and light weight properties; their reliability; and their low maintenance [13].

The major barrier to mass commercialization of this technology is the poor performance. A good thermoelectric material must have a high Seebeck coefficient (high conversion of heat to electricity) to produce the required voltage, a high electrical conductivity to reduce thermal noise, and a low thermal conductivity to reduce thermal losses. These properties are measured by the 'Factor of Merit', also known as "ZT factor". Investigation of new semiconducting materials displaying higher ZT factors is very active worldwide. At present TE materials are stuck to a ZT value around 1 and below. A broad consensus estimates a ZT factor would allow for large scale TE development [13].

Nanotechnology has been identified as the main enabler of thermoelectric efficiency improvement and thus potentially highly beneficial energy applications. However, on one hand, the increase of the Seebeck coefficient generally leads to a decrease of the electrical conductivity. On the other hand, the increase of the electrical conductivity leads to an increase of the electronic contribution

to the thermal conductivity and then to an increase of it. The improvement of nanotechnology process techniques offers possibilities to enhance the materials performances. But up to now progress remains insufficient to enable efficient energy harvesting devices. Moreover, important issues remain to be solved, namely long term nanostructure stability under high temperature and gradients [13].

Energy use reduction is the central application for TE waste heat recovery systems. These devices have a very low impact on the environment; they are totally passive, clean, and they operate without any additional energy supply. Their use in cars and public transport systems would reduce oil consumption within the limit of a few percents. Increased gasoline and diesel prices are a good market driver for seeking more sustainable and efficient technologies [13,24].

TE could provide all this and simultaneously contribute to CO_2 emission reductions in world. Additionally, TE generators could enable autonomous and wireless devices, which would possibly offer new uses and habits, and limit the requirement for electricity storage devices [13].

4.3. Photonics

Photonics is the study of the interaction of light with matter. The field was opened up in the 1960s with the invention of the laser. Ten years later, the invention of the optical fibre as a means of transmitting information via light formed the basis for optical communication. The field is now enormous and consists of many sub-disciplines and applications, like laser technology, biological and chemical sensing, display technology, optical computing, fibre optics, photonic crystals and more [11].

In 1987 Eli Yablonovitch [25] at Bell Communications Research Centre created an array of 1 mm holes in a material with a refractive index of 3.6. It was found that the array prevented microwave radiation from propagating in any direction. This discovery started the research on photonic crystals, but it took more than a decade to fabricate photonic crystals that do the same in the near-IR and visible range. Nowadays photonics crystals are an important nanomaterial investigated with numerous applications and in particular for optical communication [11].

A photonic crystal consists of a periodic structure made of dielectric materials that affects the propagation of light. Essentially, photonic crystals contain regularly repeating internal regions of high and low dielectric constant. Photons (behaving as waves) propagate through this structure—or not—depending on their wavelength. The periodicity of the photonic crystal structure has to be of the same length-scale as half the wavelength of the electromagnetic waves, i.e. ~200 nm (blue) to 350 nm (red) for photonic crystals operating in the visible part of the spectrum. Such crystals have to be artificially fabricated by methods such as electron-beam lithography and X-ray lithography [11].

Photonic crystals are now receiving much attention because of their potentials in particular in the optical-communication industry. The current explosion in information technology has been enabled by semiconductor technology and the ability to fabricate materials where the flow of electrons can be controlled in the most intricate ways. Photonic crystals promise to give us similar control over photons—with even greater flexibility because scientists have far more control over the properties of photonic crystals than they do over the electronic properties of semiconductors. The goal of putting more transistors on a chip (to make smaller and faster integrated electronic circuits) requires further miniaturization. This unfortunately leads to higher resistance and more energy dissipation, putting a limit on Moore's law. Researchers are considering using light and photonic crystals (in alternative to electrons travelling in wires) for the new generation of integrated circuits. Light can travel much faster in a dielectric medium than an electron in a wire, and it can carry a larger amount of information per second. Given the impact that semiconductor materials have had on every sector of society, photonic crystals could play an even greater role in the 21st century [11,14].

5. Conclusions

Without a doubt, ICT has played a major role in decreasing the resource intensity in society and hence has had a positive impact on environmental sustainability. At the same time, ICT has enabled and accelerated development towards more resource-consuming lifestyles, and therefore laid stress on the environment. Thus, it is fair to say that ICT is part of the problem [1]. To partly solve the problem of the rapidly increased resource consumption of ICT itself, the ICT industry has currently pushed the hardware to its fundamental physical limits. Nanotechnology promises to provide an alternative to traditional manufacturing technologies and materials, bringing the resource consumption reduction to the next level.

Nanotechnology in many respects is already a key player in ICT research and development. The industry is benefiting from nanotechnology in many ways, including from its applications in smarter sensors, logic elements, computer chips, memory storage devices, optoelectronics, and quantum computing. Not only has nanotechnology played a role in new logic and storage technologies, but it has also been identified as the main enabler of thermoelectric efficiency improvements and thus nanomaterials can be used to improve the capacity of batteries and solar cells [14]. The knowledge society expects widespread use of photonic crystals, especially in optical communications.

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